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WEDGE ABSORPTION REMOTE SENSOR†

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BY

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†Patent applied for

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The remote detection of vehicular exhaust as well as battlefield gases is of interest to the Army. Near real-time remote sensing of atmospheric gases can already be performed by using differential absorption lidar or transmission techniques. A new system called the wedge absorption remote sensor has been developed which improves integrated path detection of atmospheric gases. The wedge absorption remote sensor utilizes an emission spike train of short time

20. ABSTRACT (cont)

duration as is found in the long-pulse output mode of a solid-state laser to define the on- and off-line absorption of an atmospheric gas and, hence, its concentration. The wedge absorption remote sensor has performed well as a remote sensor of methane concentrations with an erbium:ytterbium-aluminum-garnet laser as the source.

PREFACE

The authors thank Kenneth Kunkel for his review of this report.

CONTENTS

INTRODUCTION

Lasers are already being used in the remote sensing of atmospheric gases by differential absorption techniques.[1] Lidar and transmission measurements require at present, however, that the laser source used be tuned (continuously or discretely) on and off the absorption line of the gas being sensed. Note that these tunable lasers are expensive. Also, these laser sources have repetitive pulse rates as well as changes from on- to off-line wavelengths which are slow compared to changes in the atmosphere. The net result is a decrease in the magnitude of the signal-to-noise ratio over a measurement technique which can essentially simultaneously measure the on- and off-line absorption. The value of the near simultaneous measurement technique to be described in this paper has already been demonstrated at the US Army Atmospheric Sciences Laboratory for long-pulse-mode operation of solid-state lasers albeit limited to integrated path measurements because of the few microseconds spike duration and low spike energy for each spike in the long pulse.[2] The data acquisition and display techniques required to perform these integrated path measurements have also been well documented.[3] Note also that studies of the spectral characteristics of the erbium[4,5] and holmium[6] lasers have shown that the long pulse of a solid-state laser contains a large number of spectrally narrow spikes of different wavelengths. There is a limited number of known absorption line coincidences; two examples are methane with the erbium laser and carbon dioxide with the holmium laser. As new laser sources are developed and investigated, the number and variety of gases which could be remotely sensed may increase considerably.

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[1] R. A. Baumgartner and R. L. Byer, 1978, "Continuously tunable ir lidar with applications to remote measurements of SO_2 and CH_4," Appl Opt, 17:3555.

[2] K. O. White et al, 1976, "Multiwavelength discriminator and display system for solid-state lasers," Rev Sci Instr, 47:695.

[3] K. O. White, G. T. Wade, and S. A. Schleusener, 1973, "The application of minicomputers in laser atmospheric experiments," Proceedings of the IEEE, 61:1596.

[4] S. A. Schleusener et al, 1977, "Solid-state laser wavelength identification using a reference absorber," Appl Opt, 16:2615.

[5] K. O. White et al, 1977, Solid-State Laser Wavelength Identification Using a Reference Absorber, ECOM-5820, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 21 pp.

[6] K. O. White, W. R. Watkins, and S. A. Schleusener, 1975, "Holmium 2.06 μm laser spectral characteristics and absorption by CO_2 gas," Appl Opt, 14:16.

DESCRIPTION OF THE TECHNIQUE

The wedge absorption remote sensor (WARS) employs an emission spike train as produced by the long-pulse output mode of a solid-state laser to remotely measure (using differential absorption lidar or transmission signal processing techniques) the integrated path concentration of atmospheric gases. The basic concept is to span an isolated absorption line of an atmospheric gas with the range of wavelengths of the spectrally narrow (typically < 0.0001 nm) emission spikes (typically a few microseconds duration and tens of spikes per train) in the spike train (typically a few microseconds duration). An optical beam splitter is used to obtain reference and transmitted beams. Appropriate high speed detectors are used to obtain signals for both beams. The signals are digitized with analog-to-digital converters (ADC). Comparing the ratio of the digitized reference signal to transmitted signal for each spike in the spike train yields a set of transmittance values as a function of wavelength. An example of the reference and transmitted long pulse of an erbium:ytterbium-aluminum-garnet (Er:YAG) laser absorbed by methane is shown in figure 1. Maximum absorption and hence minimum transmittance will be experienced by the spikes which have wavelengths corresponding to the center of the absorption line. Minimum absorption and hence maximum transmittance will be experienced by the spikes which have wavelengths in the far wings of the absorption line. Common to both is a background attenuation due to absorption and scattering losses which may vary with time but is nearly constant over the spectral output range of the long pulse. This attenuation can be expressed in terms of absorption coefficients as follows: the transmission T at a given wavelength is

$$T = \exp[-\alpha X] ,$$

where α is the absorption coefficient and X is the optical depth. For an off-line wavelength, the absorption coefficient α will be composed of only background absorption (α_B) or $\alpha = \alpha_B$; whereas for an on-line wavelength, the absorption coefficient α will be composed of background and line (α_L) absorption or $\alpha = \alpha_B + \alpha_L$. Hence, if the digitized reference and transmitted signals corresponding to each spike are plotted in Cartesian coordinates, a wedge of data points results. The accumulation of transmittance wedge values obtained from a few long pulses like those in figure 1 are shown in figure 2. The effect of halving the methane concentration on the data wedge is shown in figure 3. The ratio of the lower and upper slopes of the wedge is equal to the transmittance at the absorption line center (background plus maximum line absorption) divided by background transmittance (figure 4) and hence yields the product of the absorption coefficient and concentration of the absorbing gas irrespective of the background transmission level. This can be expressed

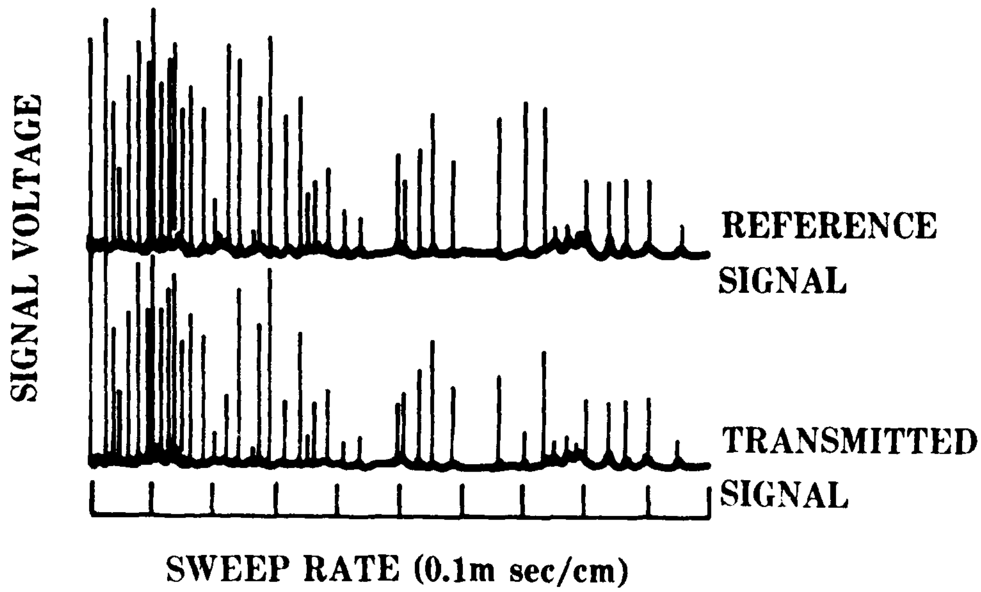

Figure 1. Dual beam oscilloscope trace of the reference (top) and transmitted (bottom) long-pulse spike train of an Er:YAG laser (y-coordinate is 2 V/cm and x-coordinate is 0.1 ms/cm.

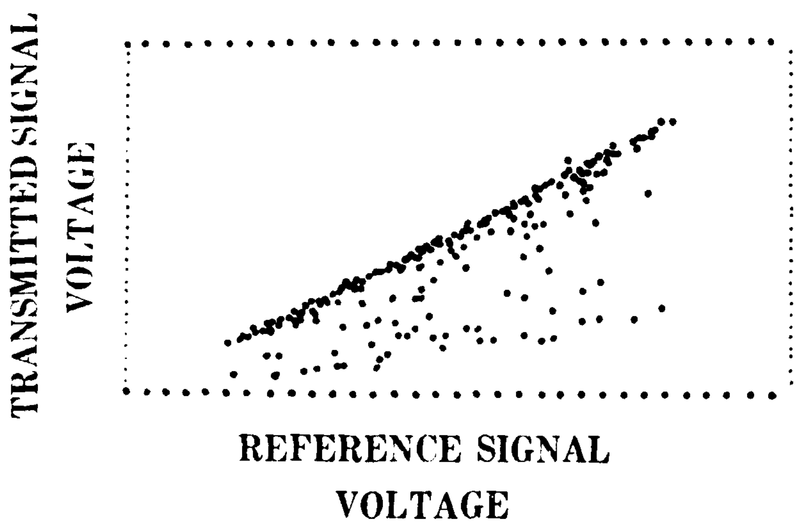

Figure 2. Cartesian coordinate display of absorption wedge representation of data from a few Er:YAG "long" pulses (relaxation pulse trains) propagated 480 m through a 760 torr total pressure atmosphere containing 0.018 torr of methane (y-coordinate is transmitted signal and x-coordinate is reference signal).

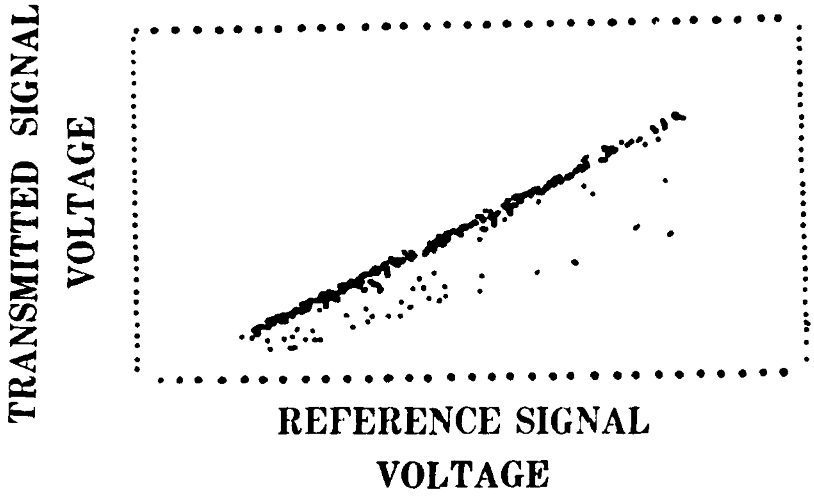

Figure 3. Cartesian coordinate display of absorption wedge collected as in figure 2 except for 0.009 torr of methane.

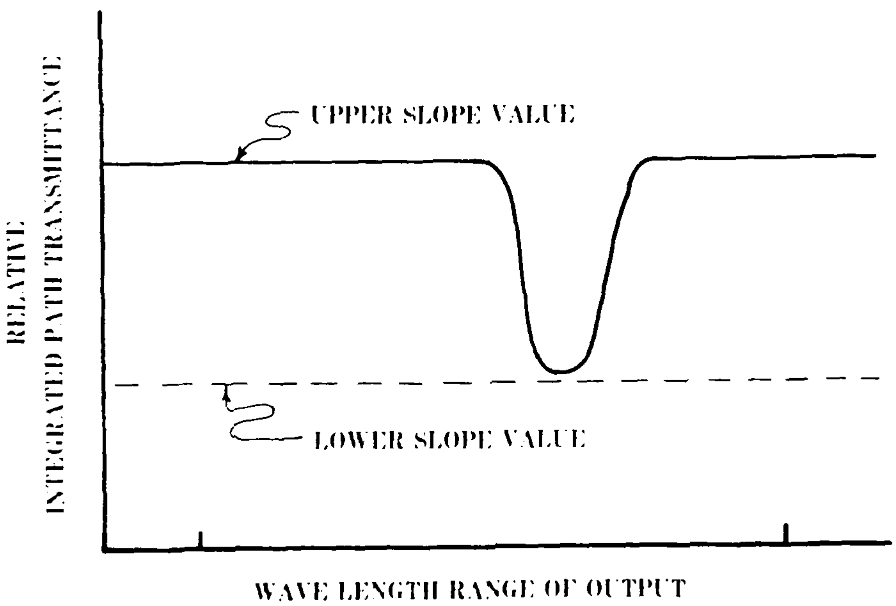

Figure 4. Representation of the decrease in transmission due to an isolated atmosphere gas absorption line spanned by the source laser output. The line center transmittance represents the lower slope of the data wedge with the background transmittance corresponding to the upper slope.

as follows where T_{ls} is the wedge lower slope (on-line) transmission and T_{us} is the wedge upper slope (off-line) transmission:

$$\frac{T_{ls}}{T_{us}} = \frac{\exp[-(\alpha_B + \alpha_L \max)X]}{\exp[-\alpha_B X]} = \exp[-\alpha_L \max X] ,$$

where α_L max represents the maximum line absorption coefficient. The advantages of the WARS over existing differential absorption lidar and transmission techniques for integrated path measurements are several. A less expensive source (for example, a solid-state laser operating in long-pulse mode) can be used instead of a tunable laser source. Data, from which gas concentration information is extracted, can be obtained during one pulse of the emission source (typically a few microseconds) during which time the atmospheric changes which usually result in poor signal-to-noise ratios are minimal. This procedure precludes having to employ costly (in terms of laser rod deterioration due to repeated Q-switched firings) time averaging of the on- and off-line signals to reduce uncertainties due to changes in the background attenuation level. Also, better sensitivity can be obtained with a weaker source because several long pulses can be easily averaged in spite of changes in the background attenuation by using each well-defined maximum transmittance slope to calibrate one set of wedge data with the next. The WARS uses essentially the same detection and data analysis schemes already used in differential absorption lidar and transmission systems.

SYSTEM DESCRIPTION

The system configuration for the WARS is shown in figure 5. Item 1 is the emission source for the spike train. An Er:YAG laser with emission about 1644.9 nm was used as the source for detecting methane. A detailed description of the laser is given elsewhere.[5] Note that when the laser rod was new it spanned the methane absorption line. In actual system use, an intracavity etalon may be needed to modify the laser wavelength output range. The long-pulse mode of the laser produced a spike train of approximately 100 spikes each of 4μs duration, within 4 ms, as can be seen in figure 1. The source beam was split into two portions by an optical flat (2) with one side antireflection-coated to eliminate secondary reflections. The major portion of the beam is propagated through the atmosphere containing the absorbing gas (3). This could represent a single or double-ended integrated path measurement. For the case of WARS system checkout, a long-path absorption cell was used. Both portions of the source beam are sensed by a detector amplifier system. For the case of the Er:YAG laser used, indium arsenide detectors were used in the reference and transmitted beam detector systems, (4) and (5), respectively. Ortec 450 amplifiers were used to amplify both detector signals to typically 2- to 10-V levels required for digitization; and depending on the application, the reference signal may have

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[5] K. O. White et al, 1977, Solid-state laser wavelength identification using a reference absorber, ECOM-5820, US Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 21 pp.

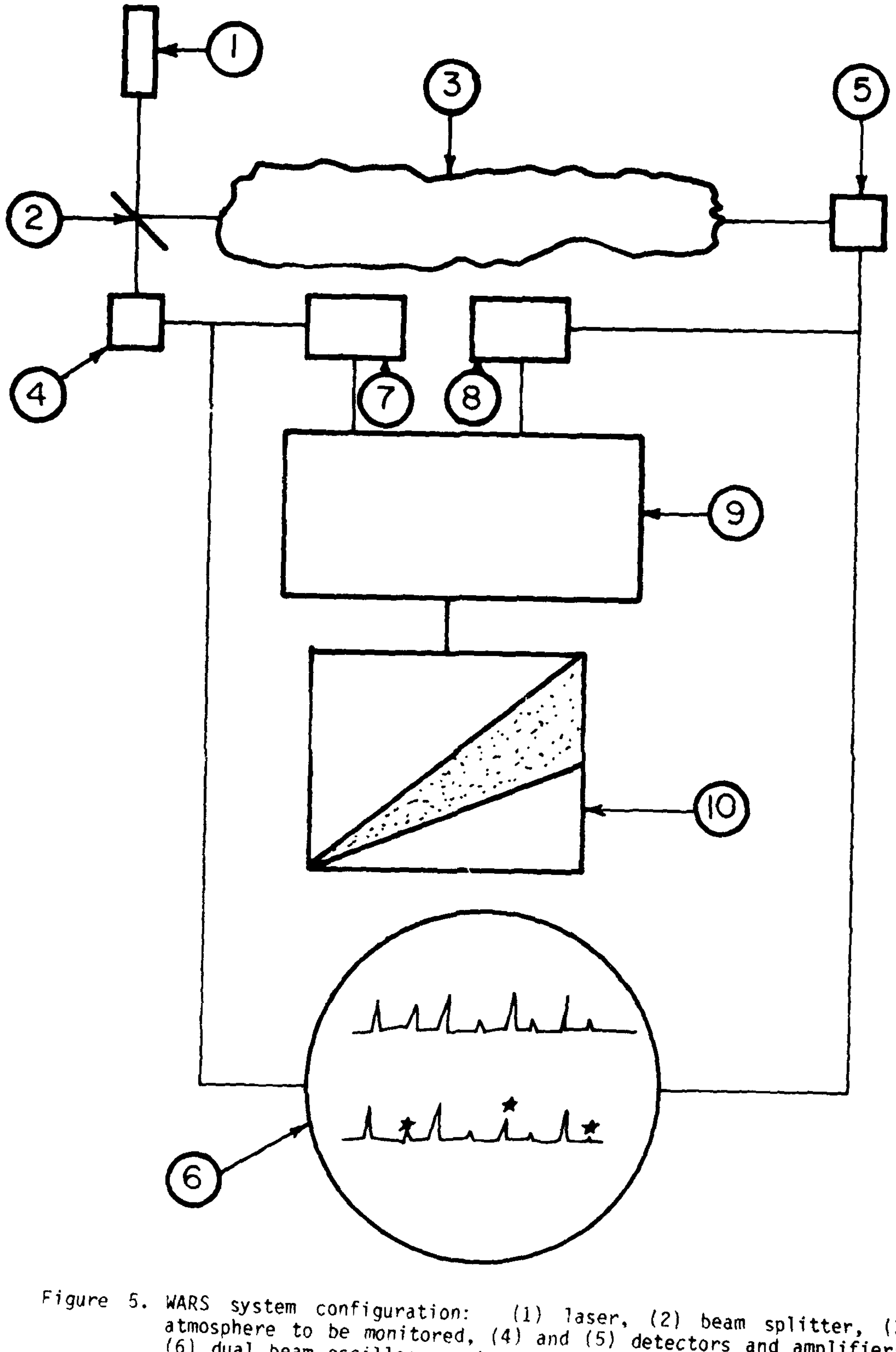

Figure 5. WARS system configuration: (1) laser, (2) beam splitter, (3) atmosphere to be monitored, (4) and (5) detectors and amplifiers, (6) dual beam oscilloscope trace of detector signals, (7) and (8) high-speed analog-to-digital converters, (9) minicomputer, and (10) xy-display of laser spike signal pairs forming the on- and off-line wedge absorption.

to be delayed to compensate for optical delay experienced by the transmitted beam over the optical path (3).

The amplified signals for the reference and transmitted spike trains can be observed on a dual beam oscilloscope (6) and adjustments made to insure proper amplification and delay. The traces shown represent a differential absorption transmission system application for integrated path transmission. The lower trace is the transmitted spike train with varying amounts of absorption in the spikes denoted by stars due to the isolated gas absorption line present. To obtain the absorption wedge from these signals, they are digitized by high-speed analog-to-digital converters (7) and (8). A minicomputer or microcomputer (9) stores the digitized reference and transmitted signals for each spike of the spike train as a data pair. A comprehensive description of this data processing system is documented in the open literature.[3] Each data pair can be displayed as a point on an xy-display (10) with the reference signal as the x-coordinate and the transmitted signal as the y-coordinate. The upper slope defined by the upper edge points in the data wedge should be made to be approximately 1.0 for best data collection and reduction by appropriate adjustment of the signal amplifiers. Both the upper and lower slope values can be obtained from this wedge of data points through software routines. The ratio of these slopes gives the transmittance for the line center absorption of the atmospheric gas of interest--in this case, methane. This transmittance can then be converted to concentration of the gas.

The WARS requires that the emission source bandwidth span (at least the line center) an isolated absorption line, but WARS is not hampered by slowly varying broadband absorption and scattering as produced by dust and particulate matter except for extreme attenuations. The system was tested by measuring varying concentrations of methane introduced into a 20-m long-path absorption cell. A change from 0.009 to 0.018 torr of methane in a 760 torr total pressure atmosphere for a 480-m pathlength was easily distinguishable (compare figures 2 and 3). Since typical atmospheric background levels of methane are on the order of 0.002 torr with a corresponding 0.1 km^{-1} absorption coefficient,[7] even these low concentration levels can be monitored by using the WARS over a 1.0 km pathlength. The WARS is ideally suited to measure changes in methane concentrations due to vehicular exhaust and potentially other battlefield gases.

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[7]K. O. White and W. R. Watkins, 1975, "Erbium laser as a remote sensor of methane," Appl Opt, 14:2812.

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